DYNAMICS OF SOLAR AND STELLAR CORONAL PLASMAS

NASA Grant NAGW-112

Final Report

For the Period 1 November 1980 through 31 October 1994

Principal Investigator
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January 1995

Prepared for:

National Aeronautics and Space Administration
Washington, D.C.

Smithsonian Institution
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The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

The NASA Technical Officer for this grant is W.J. Wagner, Code: SSS, National Aeronautics and Space Administration, Washington, D.C. .

THE ROOTS OF CORONAL STRUCTURE IN THE SUN'S SURFACE

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(Received 7 July, 1993; in revised form 13 April, 1994)

Abstract. We have compared the structures seen on X-ray images obtained by a flight of the NIXT sounding rocket payload on July 11, 1991 with near-simultaneous photospheric and chromospheric structures and magnetic fields observed at Big Bear. The X-ray images reflect emission of both Mg X and Fe XVI, formed at 1×10^6 K and 3×10^6 K, respectively. The brightest Hα sources correspond to a dying sub-flare and other active region components, all of which reveal coronal enhancements situated spatially well above the Hα emission. The largest set of X-ray arches connected plages of opposite polarity in a large bipolar active region. The arches appear to lie in a small range of angle in the meridian plane connecting their footpoints. Sunspots are dark on the surface and in the corona. For the first time we see an emerging flux region in X-rays and find the emission extends twice as high as the Hα arches. Many features which we believe to correspond to 'X-ray bright points' (XBPs) were observed. Whether by resolution or spectral band, the number detected greatly exceeds that from previous work. All of the brighter XBPs correspond to bipolar Hα features, while unipolar Hα bright points are the base of more diffuse comet-like coronal arches, generally vertical. These diverge from individual features by less than 30°, and give a good measure of what the 'canopies' must do. The Hα data shows that all the Hα features were present the entire day, so they are not clearly disappearing or reappearing. We find a new class of XBPs which we call 'satellite points', elements of opposite polarity linked to nearby umbrae by invisible field lines. The satellite points change rapidly in X-ray brightness during the flight. An M1.9 flare occurred four hours after the flight; examination of the pre-flare structures reveals nothing unusual.

1. Introduction

From the early days of coronal observations, it was clear that there is an association between the intensity and structure of the corona and the pattern of active regions on the Sun's surface. With the advent of direct imaging of the corona on the disk from sounding rockets (Vaiana, Krieger, and Timothy, 1973) and from *Skylab* (Vaiana *et al.*, 1975), that relationship became more clear. At high resolution (Webb and Zirin, 1981), one would find fairly good correlation between coronal structures and those seen in magnetograms and monochromatic chromospheric images, from coronal holes to the smallest X-ray bright points, which could be identified with bright Hα features and with He 10830 'dark points' (Harvey *et al.*, 1975).

With the advent of normal incidence imaging of the corona (Golub *et al.*, 1990; Walker *et al.*, 1988; Underwood *et al.*, 1987), a new level of resolution in the X-ray images could be obtained. To date, no systematic comparison between the

Solar Physics **153**: 179–198, 1994.

During the final year of this Grant we completed the research indicated in our Statement of Work, wrote the results in form suitable for publication and submitted them to refereed journals. The papers which were accepted for publication are:

"The Roots of Coronal Structure in the Sun's Surface", by L. Golub, H. Zirin and H. Wang, Solar Physics 153, 179 (1994).

"The Three-Dimensional Structure of X-ray Bright Points", by C. Parnell, E. Priest and L. Golub, Solar Physics 151, 57 (1994).

"Comparison Between Hot and Cool Plasma Behavior of Surges", by B. Schmieer, L. Golub and S. Antiochos, Astrophys. Journal 425, 326 (1994).

"The Magnetic Field in the Corona Above Sunspots", by D. Gary, Y. Leblanc, G, Dulk and L. Golub, Astrophys. Journal 412, 421 (1993).

"Loop Models of Low Coronal Structures", by G. Peres, F. Reale and L. Golub, Astrophys. Journal 422, 412 (1994).

THE THREE-DIMENSIONAL STRUCTURES OF X-RAY BRIGHT POINTS

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(Received 19 October, 1993; in final form 26 January 1994)

Abstract. Recently, the Converging Flux Model has been proposed for X-ray bright points and cancelling magnetic features. The aim of this peice of work is to try and model theoretically specific X-ray bright points in the framework of the Converging Flux Model. The observational data used includes a magnetogram showing the normal component of the magnetic field at the photosphere and a high-resolution soft X-ray image from NIXT showing the brightenings in the lower solar corona. By approximating the flux concentrations in the magnetograms with poles of the appropriate sign and sense, the overlying three-dimensional potential field structure is calculated. Deduction of plausible motions of the flux sources are made which produce brightenings of the observed shape due to reconnection between neighbouring flux regions. Also the three-dimensional separatrix and separator structure and the way the magnetic field lines reconnect in three dimensions is deduced.

1. Introduction

X-ray bright points (BPs) were discovered by Vaiana *et al.* (1970) from X-ray images and their basic properties were studied by Golub *et al.* (1974, 1977); Golub, Krieger, and Vaiana (1976a, b) from *Skylab* images. They form in the corona as a diffuse cloud which grows at 1 km s^{-1} up to about 20 Mm followed by the appearance of a bright core of width 3 Mm which later fades as then does the diffuse cloud. The NIXT instrument (with much less scatter) has excellent spatial resolution and shows the true size of the BPs to be much smaller than the *Skylab* images (Priest, Parnell, and Martin, 1993) revealing them as beautiful and complex structures.

Opposite polarity photospheric magnetic fragments lie below the BP. A third of these magnetic fragments are believed to be *ephemeral active regions*, small areas of emerging magnetic flux; and two thirds are believed to be *cancelling magnetic features* (Martin, 1984), bipolar regions of magnetic flux which are approaching and cancelling.

An Emerging Flux Model by Heyvaerts, Priest, and Rust (1977), modeled analytically by Tur and Priest (1976) and numerically by Forbes and Priest (1984), explains how a BP might occur in terms of reconnection between newly emerging flux and an overlying field. In a recent paper, Priest, Parnell, and Martin (1993) put forward instead a Converging Flux Model for a BP and associated cancelling mag-

Solar Physics **151:** 57–74, 1994.

THE ASTROPHYSICAL JOURNAL, 425:326–330, 1994 April 10

COMPARISON BETWEEN COOL AND HOT PLASMA BEHAVIORS OF SURGES

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Received 1993 February 24; accepted 1993 October 13

ABSTRACT

Ground-based coordinated observations with the Multichannel Subtractive Double Pass spectrograph (MSDP) allowed us to obtain chromospheric intensity and velocity field maps below coronal structures during the launch of the NIXT payload on 1991 July 11 (eclipse day). A large Hα ejection in AR 6713 (N38 W40) was detected during the NIXT flight. However, only a low level of X-ray emission was associated with this event. In contrast, bright X-ray emission associated with a subflare was observed in a nearby active region, but with only a weak associated ejection in Hα. A discussion of both of these events gives strong constraints on the triggering mechanisms of surges.

Subject headings: plasmas — Sun: activity — Sun: chromosphere — Sun: corona — Sun: magnetic fields

1. INTRODUCTION

Surge phenomena have been mainly observed in Hα using spectroheliograms or filtergrams. Some extreme ultraviolet (EUV) observations of surges were also obtained during the *Skylab* period (Schmahl 1981; Mouradian, Martres, & Soru-Escaut 1983), and during the *SMM* mission (Schmieder et al. 1983, 1984; Martres et al. 1983), and some relationships between surges and X-rays have been established by using HXIS observations (Schmieder et al. 1988, 1993; Simnett, Sotirovski, & Simon 1990; Harrison, Rompolt, & Garcynska 1988).

Different physical mechanisms have been proposed to explain the surge phenomenon. There are two main types of models: those in which the observed plasma motion is driven by gas pressure and those in which it is magnetically driven, that is, by the Lorentz force. In the pressure-driven models the basic picture is that some process raises the pressure of the deep chromosphere. This results in a sudden expansion which drives cool overlying material into the corona (e.g., Steinolfson, Schmahl, & Wu 1979; Schmahl 1981; Karpen et al. 1982; Shibata et al. 1982). In the simulations done to date the pressure enhancement at the base is taken as a boundary condition, and the thermal conditions of the driver gas are not explicitly treated. The fundamental mechanism involved in the process is not defined; for example, it could be a heating process, perhaps associated with flares. Similar ideas have been applied to spicules, which may be nothing more than small surges (e.g., Suematsu et al. 1982; Sterling & Mariska 1990; Sterling, Shibata, & Mariska 1993). In the magnetically driven models the driving force is basically an unbalanced magnetic tension that is often postulated to result from reconnection (e.g., Schlüter 1957; Carlquist 1979; Sturrock 1972; Raadu et al. 1987). Again such models have also been proposed for spicules (Blake & Sturrock 1985).

In order to understand the physical mechanism which initiates surges we have to understand the physical conditions of the plasma, both thermal and dynamical. This will help to differentiate among the various proposed models. We need observations which include both chromospheric and coronal temperatures, which of necessity means observing at different wavelengths, with good temporal and spatial resolutions. The NIXT instrument provided high-resolution full-disk coronal images at 63.5 Å out to 1.3 solar radii above the limb. Data were taken on 1991 July 11 exactly simultaneous with eclipse totality as seen from Hawaii. Many ground-based observatories were taking data during that time, and it is a good opportunity to understand the way in which the outer coronal structures connect to the solar surface. The Multichannel Subtractive Double Pass spectrograph (MSDP) operating at the Meudon Solar Tower observed simultaneously with the NIXT instrument and allows us to obtain information on the chromospheric activity as well as on the dynamics of the cool plasma inside the chromospheric structures.

We focus our attention on active region AR 6713 (N38 W42), in which two separate transient events were taking place during the time of the observations. In one event there are seen several bright structures in X-rays associated with a subflare, and in the other there are seen prominent Hα features associated with a large extended ejection of cool material. The comparison of these two events and their respective signatures in cool and hot plasma may provide a key to understanding the mechanism for ejection of material. After describing the active region and comparing the structures in Hα and in X-rays we will discuss the possible mechanisms for the ejection driver.

2. INSTRUMENTS

2.1. *NIXT*

The Normal Incidence X-ray Telescope (NIXT) was launched on a NASA sounding rocket from White Sands Missile Range at 17:25 UT (see the times of the observations in Table 1). On the first image the Moon occults a part of the corona several arcminutes off the Western limb, and by the end of the flight the Moon is just approaching first contact. The NIXT instrument observes the full disk of the Sun with a resolution less than 1″; it is described in detail by Spiller et al. (1991). The multilayer mirror has a passband of 1.4 Å at 63.5 Å the wavelength of emission lines of Mg X and Fe XVI that are formed at temperatures $T \sim 10^6$ K and 3×10^6 K, respectively.

A portion of a NIXT image, taken at 17:27 UT is shown in Figure 1 (Plate 10). The figure shows the northeast quadrant of the corona on that day, including the region in and around AR 6713 which is the subject of this paper.

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THE ASTROPHYSICAL JOURNAL, 422:412–415, 1994 February 10

LOOP MODELS OF LOW CORONAL STRUCTURES OBSERVED BY THE NORMAL INCIDENCE X-RAY TELESCOPE (NIXT)

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ABSTRACT

The X-ray pictures obtained with the Normal Incidence X-Ray Telescope (NIXT), apart from the ubiquitous coronal loops well known from previous X-ray observations, show a new and peculiar morphology: in many active regions there are wide and apparently low-lying areas of intense emission which resemble Hα plages.

By means of hydrostatic models of coronal arches, we analyze the distribution of temperature, density, emission measure, and plasma emissivity in the spectral band to which NIXT is sensitive, and we show that the above morphology can be explained by the characteristics of high pressure loops having a thin region of high surface brightness at the base. We therefore propose that this finding might help to identify high-pressure X-ray emitting coronal regions in NIXT images, and it is in principle applicable to any imaging instrument which has high sensitivity to 10^4–10^6 K plasma within a narrow coronal-temperaure passband.

As a more general result of this study, we propose that the comparison of NIXT observations with models of stationary loops might provide a new diagnostic: the determination of the loop plasma pressure from measurements of brightness distribution along the loop.

Subject headings: Sun: chromosphere — Sun: corona — Sun: X-rays, gamma rays

1. INTRODUCTION

The program of solar X-ray observations with grazing incidence telescopes, made by the AS&E solar group in the 1960s and early 1970s, provided for the first time a clear and comprehensive description of the solar X-ray corona as entirely composed of loops of magnetically confined hot coronal plasma of different sizes and physical conditions (Vaiana, Krieger, & Timothy 1973). This picture was entirely confirmed by the subsequent observations made with the S-054 X-ray telescope on board *Skylab* (Vaiana & Rosner 1978) and other broad-band soft X-ray observations at high spatial resolution. Since then, the paradigm that the corona is entirely formed by magnetic loops confining the emitting plasma has been commonly accepted and extended also to the coronae of solar-like stars.

More recently, the Normal Incidence X-Ray Telescope (NIXT) (Golub et al. 1990; Golub 1992) has been used to observe the Sun in five rocket flights. Among many other features, NIXT pictures of active regions show a new X-ray morphology: low-lying regions of X-ray emission which resemble Hα plage and do not appear similar to loops. By means of detailed models of static loops, we show that such an effect can be explained with the physics of coronal loops as very intense emission in the NIXT band from the base of high-pressure loops. The bright, low-lying emission is due to the peculiar nature of the NIXT temperature sensitivity, with its bimodal temperature response. We discuss the implications of this finding and the diagnostics which stem from it.

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2. THE TELESCOPE AND THE OBSERVATIONS

NIXT is based on multilayer normal incidence mirrors whose layers work interferentially to produce high reflectivity in a narrow spectral band (Barbee 1981; Spiller 1990). The spectral response of the system is centered on 63.5 Å and the bandwidth is 1.4 Å, including intense Mg X and Fe XVI soft X-ray lines within the band. Figure 1 presents the coronal thermal emissivity versus temperature of a hot solar plasma, filtered through the response of NIXT.

This telescope is characterized by a much lower scatter than obtained with grazing incidence telescopes (Golub & Spiller 1992) and achieves better angular resolution, namely, below 1″. So far, picture resolution has been limited to slightly less than 1″ by the grain of the photographic film used to register the images. The mirror diameter is 27.5 cm, and the optical scheme is an f/8 prime focus. The telescope has to date been flown exclusively on sounding rockets.

In addition to the ubiquitous presence of the expected coronal loops, NIXT pictures show an apparently peculiar morphology (see Fig. 2 [Pl. 1]), characterized by broad and apparently shallow regions of emission which resemble underlying Hα plages and certainly not loops. We can safely exclude that such a morphology is produced by contamination from stray UV emission from the chromosphere, for istance, the very intense He 304 Å line, because the filters in front of the detector contain carbon to such an extent as to absorb all UV radiation and because the photographic film is not sensitive to UV. Moreover, there are many bright Hα patches which do *not* have corresponding bright features in the NIXT images, so that it is not a simple transfer of chromospheric visibility into the X-ray images.

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THE ASTROPHYSICAL JOURNAL, 412:421–430, 1993 July 20

THE MAGNETIC FIELD IN THE CORONA ABOVE SUNSPOTS AT THE ECLIPSE OF 1991 JULY 11

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Received 1992 October 1; accepted 1993 January 26

ABSTRACT

We have used the frequency-agile solar array at the Owens Valley Radio Observatory (OVRO) and the rocket-launched soft X-ray imager NIXT to observe the corona above an active region during the solar eclipse of 1991 July 11. The uncovering of the active region AR 6718 by the Moon allows us to obtain an angular resolution of 1".8 over the frequency range of the OVRO telescope, 1–18 GHz, comparable to the less than 1" resolution of NIXT.

The dominant features of AR 6718 are two leading spots of positive polarity followed by two spots of negative polarity ~3' to the east. Bright ($T_b \approx 2 \times 10^6$ K) radio emission coincides with the positions of the sunspots, attributable to gyroresonance radiation from ambient electrons above the spots. Using a simplified model of the source as a function of frequency based on the interferometer fringe amplitudes, we obtain brightness temperature spectra for the emission associated with the sunspots. From these data we are able to deduce that the magnetic field strength at the base of the corona above the leading spots was ~1200 G, and ~1100 G above the following spots. The magnetic field spreads and its strength decreases with height in the corona, with the 1200 and 360 G fields covering areas of ~15" and 28" in diameter, respectively. Lower down, in the transition region where $T_e \approx 2$ to 3×10^5 K, the field strength was ~1800 G.

The soft X-ray brightness above the sunspots was very low, ~30 times lower than that of the adjacent plage-associated emission. From the X-ray data, supplemented by the electron temperature derived from the radio data, we find that the electron density at the base of the corona above the sunspots was $\approx 1 \times 10^9$ cm^{-3}. Combining the X-ray and radio data,, we derive an upper limit to the gradient of field strength with height: $|\nabla B| \lesssim 1.5 \times 10^{-6}$ G cm^{-1}.

Subject headings: eclipses — Sun: corona — Sun: magnetic fields — sunspots

1. INTRODUCTION

The magnetic field in the solar corona is poorly known because there are few kinds of observations that can measure it unambiguously. It has not been measured with confidence from Zeeman splitting of coronal lines. Extrapolations from the photospheric magnetic field are valuable in some circumstances, but they do not take into account electric currents in the corona and their associated fields. The field in active regions prominences has been inferred from several direct and indirect methods such as requirements for stability, thermal insulation, forms of loops, oscillations, and the Hanle effect. These measurements indicate that few or no prominences have field strengths above 150 G, and typical strengths are 26 G (Harvey 1969). These observations apply to the field within active regions, but not the field above sunspots. During flares, microwave radio observations have been used by many authors to estimate the magnetic field in the regions containing the high-energy electrons. Typical values obtained apply to a higher region of the corona than is relevant here, often away from sunspots.

The most reliable information on the magnetic field in the corona above sunspots probably comes from microwave observations between ~3 and 15 GHz. In this frequency range, bright emission is often observed, emission that is localized above and near sunspots; it is reliably attributed to gyroresonance radiation at the second and third harmonics of the gyrofrequency (e.g., Kakinuma & Swarup 1962; Zheleznyakov 1962; Takakura 1972; Ramaty & Petrosian 1972; Lee, Gary, & Hurford 1993a). High-resolution observations by the Westerbork and Stanford interferometers, with the RATAN 600, and with the VLA,[5] mostly near 5 GHz, have confirmed the role of gyroresonance emission by showing vividly that radiation of high brightness temperature, $T_B \gtrsim 10^6$ K, and high degree of circular polarization (up to 100%) is localized above sunspots (e.g., Alissandrakis, Kundu, & Lantos 1980; Krüger et al. 1986; Alissandrakis, Kundu, & Shevgoankar 1991), or found in a sort of ring structure near them (Pallavicini et al. 1979; Shibasaki et al. 1983; Alissandrakis & Kundu 1982; Lang & Wilson 1982).

At frequencies lower than ~3 GHz the same localization of emission is not observed. Instead, radiation of $T_B \gtrsim 10^6$ K covers most or all of the active region. This radiation is of low polarization ($\lesssim$20%), and has been convincingly attributed to free-free emission from the hot, dense electrons that are confined in the strong magnetic field (Chiuderi-Drago, Felli, & Tofani 1977; Dulk & Gary 1983; Lang & Wilson 1983). This is not to say that gyroresonance radiation does not occur at these

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[5] The VLA is a facility of the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under contract with the National Science Foundation.

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